Simultaneous parametric oscillation and signal-to-idler conversion for efficient downconversion

Gil Porat,* Ofer Gayer, and Ady Arie

Department of Physical Electronics, Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel
Corresponding author: gilporat@post.tau.ac.il

We experimentally demonstrate an optical parametric oscillator, whose signal pumps another difference-frequency generation process. Engineered idler frequency coincidence of both processes in a single quasi-periodic crystal improves pump-to-idler slope efficiency by 52.8%, from 15.25% to 23.3%, and pump-to-idler conversion efficiency (at an average pump power of 1.2 W) by 16.6%, from 12.5% to 14.58%. © 2010 Optical Society of America

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Tunable and coherent IR radiation is commonly provided by a quasi-phase-matched optical parametric oscillator (OPO) [1] pumped by a laser of frequency ω_p, generating signal frequency ω_s and idler frequency ω_i, satisfying $\omega_p = \omega_s + \omega_i$. The quantum efficiency of the frequency downconversion process of the laser light to longer wavelengths poses a limit to the overall efficiency of the OPO. For example, the quantum efficiency of converting $\lambda_p = 1$ μm to $\lambda_i = 4$ μm is $\eta_q = \lambda_p/\lambda_i = 25\%$.

Efficiency enhancement as well as generation of additional wavelengths has been theoretically and experimentally demonstrated by phase-matching an additional cascaded frequency conversion processes in the same cavity [2–5] or in single-pass configurations [6,7]. This enhancement can be obtained by using the signal wave of a downconversion process (e.g., OPO) to pump an additional difference frequency generation (DFG) process, where the latter generates energy at the idler frequency of the former. This was done by using multiple crystals or poling separate zones of the same crystal with different periods. Simultaneous phase matching of cascaded processes in an OPO cavity has experimentally generated an additional wavelength [8]; however, it has not yet been used to enhance the OPO conversion efficiency. It has also been theoretically shown [9] that using a single aperiodic crystal, which phase matches both processes, can improve the conversion efficiency from a 1.064 μm pump to a 2.8 μm idler and an additional 4.3 μm wave.

In this Letter, we employ the scheme of quasi-phase matching in the same crystal: in addition to the OPO process, a DFG process which converts signal energy into idler energy, and an additional frequency named signal2, satisfying $\omega_s = \omega_{s2} + \omega_i$. The two processes are simultaneously phase matched by using a quasiperiodic design. This scheme is experimentally compared with the standard OPO, which is based on a single conversion process of the pump wave to the idler wave. It is found that the two simultaneous processes configuration has higher pump to idler conversion efficiency and slope efficiency (i.e.,

the slope of the idler power versus pump power plot, for pump power well above oscillation threshold).

Employing the slowly varying envelope and plane-wave approximations, the following coupled wave equations for all four interacting waves are obtained, where the OPO signal acts as the pump source of the DFG process, and the OPO idler wavelength coincides with the DFG idler wavelength:

$$\frac{dA_p}{dz} = -\frac{\alpha_p}{2}A_p(z) + \kappa_{\mathrm{OPO},p}(z)A_s(z)A_i(z)e^{-i\Delta k_{\mathrm{OPO}}z}, \quad (1)$$

$$\frac{dA_s}{dz} = -\frac{\alpha_s}{2}A_s(z) + \kappa_{\mathrm{OPO},s}(z)A_p(z)A_i^*(z)e^{i\Delta k_{\mathrm{OPO}}z}$$
$$+ \kappa_{\mathrm{DFG},s}(z)A_{s2}(z)A_i(z)e^{-i\Delta k_{\mathrm{DFG}}z}, \quad (2)$$

$$\frac{dA_i}{dz} = -\frac{\alpha_i}{2}A_i(z) + \kappa_{\mathrm{OPO},i}(z)A_p(z)A_s^*(z)e^{i\Delta k_{\mathrm{OPO}}z}$$
$$+ \kappa_{\mathrm{DFG},i}(z)A_s(z)A_{s2}^*(z)e^{i\Delta k_{\mathrm{DFG}}z}, \quad (3)$$

$$\frac{dA_{s2}}{dz} = -\frac{\alpha_{s2}}{2}A_{s2}(z) + \kappa_{\mathrm{DFG},s2}(z)A_s(z)A_i^*(z)e^{i\Delta k_{\mathrm{DFG}}z}, \quad (4)$$

where $\Delta k_{\mathrm{OPO}} = k_p - k_i - k_s$ and $\Delta k_{\mathrm{DFG}} = k_s - k_i - k_{s2}$. The indices p, s, i, and $s2$ indicate the pump, signal, idler, and signal2, respectively. A_j, α_j, w_j, and k_j are the amplitude, power attenuation per unit length, frequency, and wavenumber of wave j, respectively. $\kappa_{\mathrm{OPO},j}(z) = i\omega_j d_{\mathrm{OPO}}g(z)/cn_j$ and $\kappa_{\mathrm{DFG},j}(z) = i\omega_j d_{\mathrm{DFG}}g(z)/cn_j$ are the OPO and DFG process coupling coefficients for wave j, respectively. $g(z)$ is a unitless modulation function of the nonlinear coefficient $\chi^{(2)}$. $d_{\mathrm{OPO}} = 1/2\chi^{(2)}_{\mathrm{OPO}} = 20.025$ pm/V and $d_{\mathrm{DFG}} = 1/2\chi^{(2)}_{\mathrm{DFG}} = 19.144$ pm/V are the OPO and DFG nonlinear coefficients, respectively, calculated using Miller's rule [10,11].

The nonlinear coefficient of a 40-mm-long, 11.26-mm-wide, and 1-mm-thick 5% MgO-doped congruently grown LiNbO$_3$ (MgCLN) crystal was modulated by electric field poling. The optimum conversion efficiency was designed to be obtained at a temperature of 125°C for pump, signal, signal2, and idler wavelengths $\lambda_p = 1.064$ μm, $\lambda_s = 1.456$ μm, $\lambda_{s2} = 2.307$ μm, and $\lambda_i = 3.950$ μm, respectively. Using the Sellmeier equation of Gayer *et al.* [12] we calculated phase mismatches of $\Delta k_{\mathrm{OPO}} = 0.218$ μm^{-1} and $\Delta k_{\mathrm{DFG}} = 0.191$ μm^{-1}.

The quasi-periodic crystal was designed using the dual-grid method (DGM) [13]. This method provides a systematic algorithm for modulating the nonlinear coefficient of the crystal, so that it will simultaneously phase match different interactions with arbitrary phase-mismatch values. For the case considered here, this will result in longer and overlapping interaction lengths for both processes as compared to two cascaded periodically poled gratings, for a given crystal length. The quasi-periodic lattice is composed of two basic building blocks, with lengths $l_a = 16.27$ μm and $l_b = 14.30$ μm. By numerical optimization we have found that highest efficiency is obtained when block a has (say) positive nonlinearity and block b has the opposite negative nonlinearity, as described in the inset of Fig. 1. The optimization procedure assumed that the highest efficiency is obtained when the sum $G_{\mathrm{OPO}}^2 + G_{\mathrm{DFG}}^2$ is maximized (subject to fabrication restraints regarding minimal domain size of 7 μm), where G_{OPO} and G_{DFG} are the Fourier coefficients corresponding to the OPO and DFG processes, respectively. From the Fourier transform of the quasiperiodic lattice shown in Fig. 1, we deduce that $G_{\mathrm{OPO}} = 0.3996$ and $G_{\mathrm{DFG}} = 0.3994$. For comparison, the highest Fourier coefficient in case of a periodic modulation is $2/\pi \approx 0.63$.

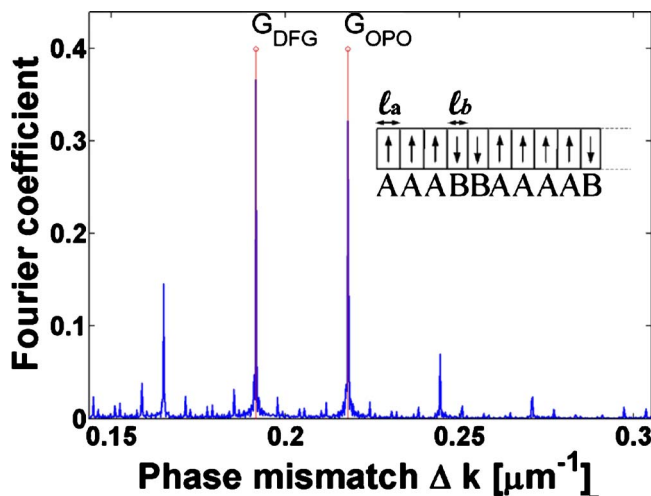The two nonlinear processes were characterized independently. The pump-to-idler conversion process ($w_p - w_i \rightarrow w_s$) was characterized by applying the pump and idler waves of an additional OPO into the crystal, and measuring the signal wave power generated by the crystal. The signal-to-idler conversion process ($w_s - w_i \rightarrow w_{s2}$) was characterized by applying the signal and idler waves of an additional OPO into the crystal, and measuring the signal2 wave power generated by the crystal. Owing to coating damage, the second experiment could not be performed on the quasi-periodic grating. Instead, it was performed using a grating composed of two periodically poled zones of equal (20 mm) length: one phase matches the pump-to-idler conversion process, and the other phase matches the additional DFG process. This grating was fabricated on the same crystal as the quasi-periodic grating, and the two periods were chosen to quasi-phase match Δk_{OPO} and Δk_{DFG}; therefore, it provides the same temperature and wavelength dependence of the signal to idler conversion process.

These two experiments were repeated for different temperatures of the crystal. Figure 2(a) shows that the two processes are simultaneously phase matched for the same wavelengths when the crystal tempera-
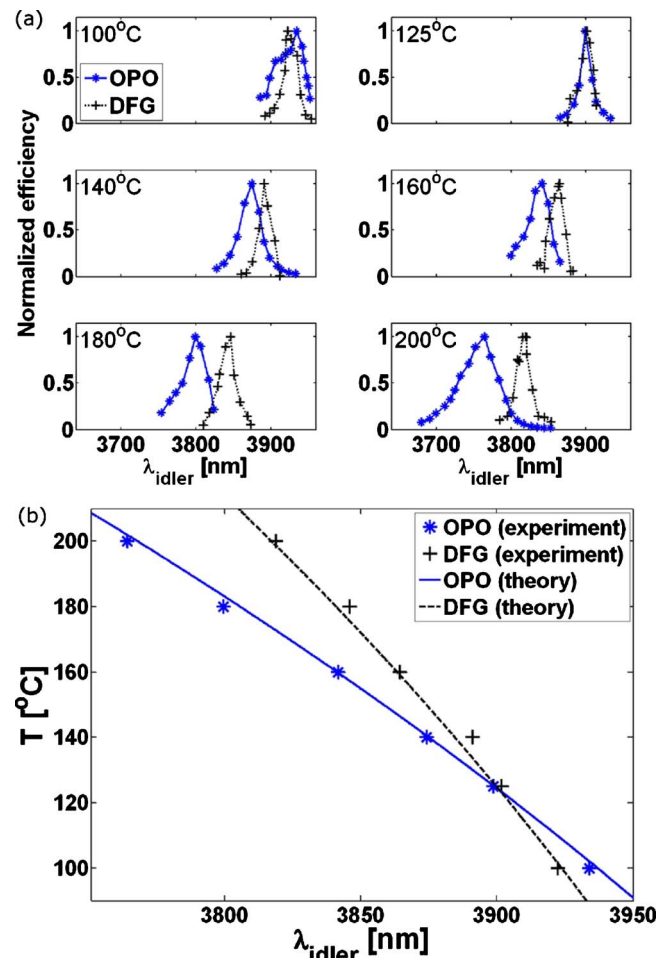

Fig. 2.   (Color online) (a) Normalized efficiency of OPO (solid line with blue stars) and DFG (dashed line with black crosses) processes versus idler wavelength at different crystal temperatures. (b) Locus of processes peaks in the crystal temperature-idler wavelength plane. The theoretical curves have been downshifted by 37.7 nm to account for Sellmeier and temperature inaccuracies.

Fig. 1.   (Color online) Fourier transform of the quasi-periodic lattice. The first order Fourier coefficients are $G_{\mathrm{OPO}} = 0.3996$ and $G_{\mathrm{DFG}} = 0.3994$. The inset shows part of the quasi-periodic lattice, composed of building blocks of lengths $l_a = 16.27$ μm and $l_b = 14.30$ μm.

ture is near the designed value of 125 °C. Figure 2(b) shows the locus of the peaks of each process in the T-λ_{idler} plane, for both the experimental results and the theoretical prediction. The theoretical curves have been downshifted by 37.7 nm. This nearly constant difference between experiment and theory is due to inaccuracies in the Sellmeier equation and in determining the crystal temperature.

The 40 mm crystal was placed in a 55-mm-long linear cavity made of two mirrors with a 50 mm radius of curvature, pumped by a 5.5 ns Nd:YAG laser with a repetition rate of 10 kHz. The OPO is single-pass singly resonant; i.e., the output coupling mirror partially reflects the signal beam only. The output mirror's signal reflectance is ∼90%, as this was the highest reflectivity the manufacturer was able to obtain while maintaining high pump and idler transmittance. Round-trip cavity loss for the signal is estimated to be 12.4%. The pump beam waist radius was 105 μm in the center of the cavity. Signal, signal2, and idler waist radii are estimated to be 105, 132, and 170 μm, respectively.

Figure 3 shows the average output idler power obtained from a periodic grating and a quasi-periodic grating fabricated on the same crystal. The peak power is ≈1.7×10^4 times higher than the average power. Since both gratings achieve parametric oscillation at pump power levels well below 600 mW, we calculate the slope efficiency as the slope of the plot starting at this point. The periodic grating yields a slope efficiency of $\eta_{s,OPO} = 15.25\%$, with a corresponding efficiency of 12.5% for $P_{pump} = 1.2$ W, generating 150 mW of idler power. The quasi-periodic grating's slope efficiency is $\eta_{s,QP} = 23.3\%$, resulting in 14.58% efficiency for $P_{pump} = 1.2$ W. Hence the idler power is 175 mW, i.e., a 16.6% improvement over the performance of the periodic OPO grating. The great improvement, of 52.8%, in slope efficiency means that as the pump power is increased, the improvement in conversion efficiency will also increase. At present
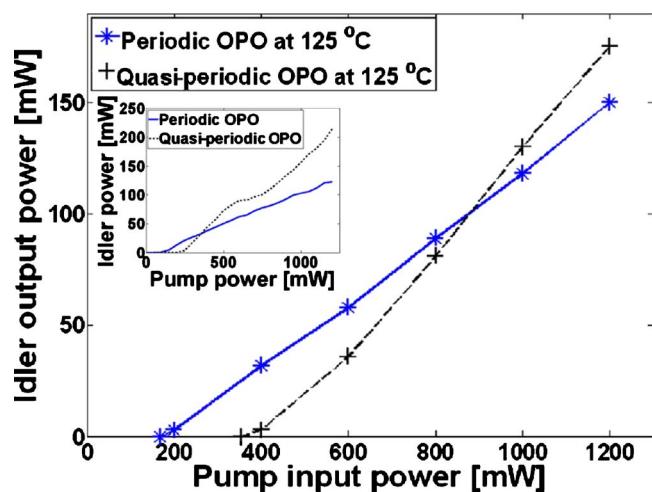

Fig. 3. (Color online) Experimentally measured average idler output power of periodic OPO and quasiperiodic OPO. Inset, simulation results for the same configurations.

damage to the crystal coating sets the limit to the pump power. The higher threshold of the quasi-periodic OPO is caused by the requirement that the same crystal quasi-phase matches an additional process.

The inset of Fig. 3 shows simulation results for the same configuration. The simulation is based on the split-step Fourier method [14] and takes into account beam diffraction. Its results repeat the main properties of the experiment, i.e., an increase in both slope efficiency and threshold power for the quasi-periodic grating as compared to the periodic grating. The reduction in simulated efficiency around pump power of 600 mW is attributed to increased backconversion of the idler to the pump. It was not apparent in the experimental results, which were generally of lower efficiency, since the simulation does not take into account additional parasitic processes (e.g., second-harmonic generation) that drain energy from the pump, signal, and idler. Actual poling quality could also degrade experimental results.

To conclude, we have shown experimentally for the first time, to the best of our knowledge, that a single quasi-periodic crystal that simultaneously phase matched pump-to-idler and signal-to-idler processes improved the pump-to-idler conversion efficiency from 12.5% to 14.58% (16.6% improvement) and the slope efficiency from 15.25% to 23.3% (52.8% improvement). The same method can be used to enhance OPO conversion efficiency for any set of pump, signal, and idler wavelengths. Moreover, this method can be further extended by additional cascaded processes, each pumped by the signal of another, and all having the same idler wavelength.

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